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Measurements of Heavy Quark Production at DØ

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Abstract

We report measurements of the inclusive single muon and b-quark cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the D0 detector at the Fermilab collider, for the kinematic range $|y_b| < 1.0$ and $p_t^b > 6$ GeV/c. We also report preliminary measurements on the J/ψ and Υ production cross sections.

1. Introduction

The D0 experiment at the Fermilab Tevatron has measured the inclusive single muon cross section for $|\eta_\mu| < 0.8$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using data taken during the 1992-93 collider run. The b-quark cross section is extracted using these measurements and found to be in agreement, within experimental error and theoretical uncertainty, with next-to-leading order QCD predictions, though all of the data are systematically high with respect to the prediction. The inclusive J/ψ and Υ cross sections in the central region have also been measured. These results are similarly high with respect to theoretical expectation.

The D0 detector has been described elsewhere [1]. It consists of inner tracking chambers used to measure the primary vertex and to help identify electrons and muons, uranium-liquid argon calorimeters to detect electrons, photons and jets, and iron toroids and drift chambers to detect muons. The combined calorimeter plus toroid thickness varies from about 14 λ in the central region to 19 λ in the end. This thickness reduces the punchthrough backgrounds to less than 1% of prompt muon production and also allows for clean muon identification within hadronic jets. Muon momentum is measured using the toroid and has a

resolution of $\sigma(p)/p = 0.18(p - 2)/2 \oplus 0.008p$ (where p is in GeV/c).

2. The b Quark Cross Section Analysis

We have measured b-quark production cross section using the semileptonic decays $b \to \mu + X$. For this paper, only results from the central region with $|\eta_\mu| < 0.8$ are presented. Events were collected using a single muon trigger which required a coincidence in the level 0 beam-beam scintillation counters which indicated that an inelastic collision had occured. The level 1 muon trigger uses 60 cm wide hodoscopic elements formed from the muon drift chambers, and required 2 or 3 layers of chambers to have hits consistent with a muon produced in the interaction region. The minimum energy of muons exiting the toroid is about 3.2 GeV and the level 1 muon trigger became fully efficient at 5 GeV. At level 2, muons are identified using a software filter composed of the initial part of the offline reconstruction. The single muon trigger requires one or more muons at level 1 and level 2, while the dimuon trigger used in the J/ψ and Υ analyses requires two or more at each level.

Good muons were selected offline by requiring each muon to have hits in all three layers of the muon system for the single muon cross section analyses (this requirement is relaxed by one for the dimuon cross

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section). Additionally each muon was required to have at least 1 GeV of associated calorimeter energy, possess a matching track in the central tracking chamber, point back to the interaction vertex in the bend and non-bend views, and traverse a minimum field integral of 0.6 GeV/c in the toroids.

All muons were required to have $|\eta^\mu| < 0.8$. Additional kinematic cuts applied were $p_t^\mu > 3.5$ GeV/c for the single muon analysis, and $p_t^\mu > 3$ GeV/c for the dimuons. The J/ψ analysis requires that all dimuons have invariant mass $M_{\mu\mu} < 6$ GeV/c^2 while the Υ requires invariant mass > 6 GeV/c^2. In addition, the Υ analysis makes a cut on the 3-space opening angle between the muons to remove cosmic ray background, $\Phi_{3d} < 160°$, and requires that each muon appear isolated in the calorimeter. The isolation parameter, I, is defined as the difference between the energy observed in the calorimeter in a cone of $R = 0.2$ in $\eta - \phi$ space about the muon, minus the expected energy, divided by the error on that expectation:

$$I = \frac{E_{observed} - E_{expected}}{\sigma_e} \qquad (1)$$

For these analyses, residual cosmic ray contamination was estimated by fitting the crossing time distribution in the muon chambers (called floating T0) to distributions of known beam produced muons and cosmic rays. In all analyses the remaining cosmic ray contamination is approximately 10%. After all cuts, the number of single muon events is 16000 from 73 nb^{-1} of data. For the Υ and J/ψ analyses, there were 540 events from 7.3 pb^{-1}, and 1740 events in 6.6 pb^{-1}, respectively.

Trigger and offline selection efficiencies were determined by passing Monte Carlo events through the full D0 detector, trigger simulation, and reconstruction packages. In all cases the efficiencies were cross-checked using appropriate data samples.

The resulting single muon cross section is shown in Figure 1 compared to expectation for contribution from π/K and W/Z decays from ISAJET. The excess in the data compared to the prediction for these sources we attribute to muons from the decay of heavy (b/c) quarks. The fraction of the inclusive muon spectrum originating from b-quark decay was estimated by fitting the distributions of muon p_t relative to the nearest reconstructed jet axis (p_t^{rel}) with the p_t^{rel} shapes predicted by ISAJET for muons from the decays of b, c, and π/K sources. p_t^{rel} is a quantity which depends upon the Q value of the decay, and is relatively insensitive to the details of the particular Monte Carlo involved. About 60% of the events in the inclusive single muon sample reconstuct a jet of $E_t > 8$ GeV within a cone of $R = 0.7$ in $\eta - \phi$ space about the muon. This fraction is consistent with predictions from simulations, and all kinematic distributions for the samples with
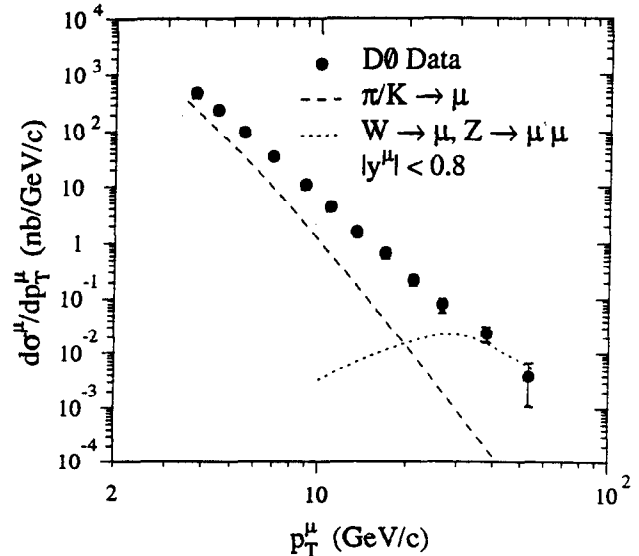

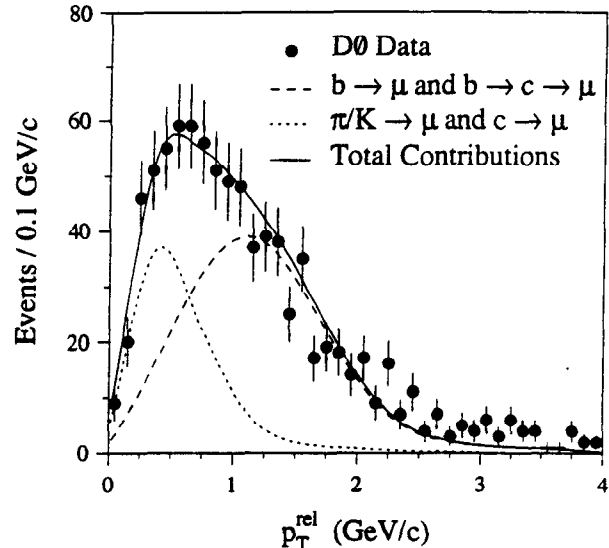Figure 1. The single muon cross section vs. p_t^μ for muons with $|\eta| < 0.8$.

Figure 2. P_t^{rel} distribution for muons with p_t^μ in the range $8 < p_t < 30$ GeV/c, and $|\eta^\mu| < 0.8$.

and without recontructed jets have been checked to be similar. The b fraction extracted from this method is thus assumed to hold for the entire sample. The result of one of the p_t^{rel} fits to a single bin of the inclusive muon p_t spectrum of Figure 1 is shown in Figure 2. The results of the p_t^{rel} fits to each of the bins of the inclusive spectrum is shown in Figure 3. The fitted points are compared to the b fraction extracted by calculating the b fraction directly, assuming the b/c ratio present in ISAJET. The two methods give consistent results, predicting a b fraction of about 25% for muons with $p_t^\mu \simeq 5$ GeV/c, rising to about 80% for muons with $p_t^\mu > 15$ GeV/c. For both methods, the contribution from W/Z decay was calculated directly using the D0 measured cross sections, and subtracted from the data prior to the fitting procedure.

Once the fractions of the single muon inclusive cross sections coming from b-quark decay is determined,
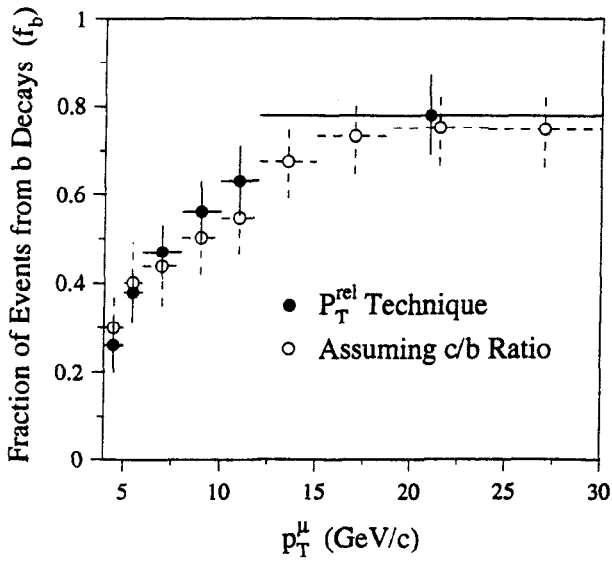
Figure 3. f_b as a function of p_t^μ: the solid points are from the P_t^{rel} fitting technique and the open circles are from the b/c ratio method.
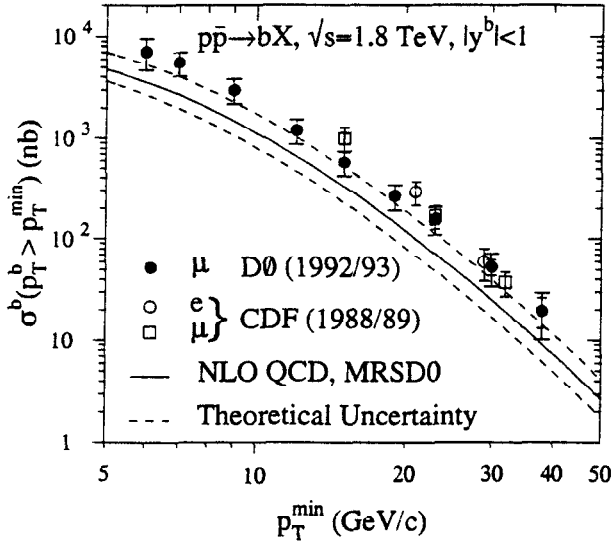

Figure 4. The b-quark cross section vs. k_t^{min} for the single muon analysis.

the integrated inclusive b-quark cross section can be extracted following the method of UA1 and CDF in order to facilitate comparison [2, 3]. The resulting b-quark cross section is plotted in Figure 4 The results are consistent with the next-to-leading order (NLO) QCD calculations of Nason *et al.* [4], within experimental errors and theoretical uncertainty, though all of the data points are systematically high relative to the prediction. the range of theoretical uncertainty shown in Figure 4 is obtained by varying the renormalization μ and the Λ parameter within the range $\mu_0/2 < \mu < 2\mu_0$ and $100 < \Lambda < 187$ MeV.

3. Inclusive J/ψ Cross Section

To select J/ψ candidates, each muon was required to pass similar track quality criteria as in the dimuon
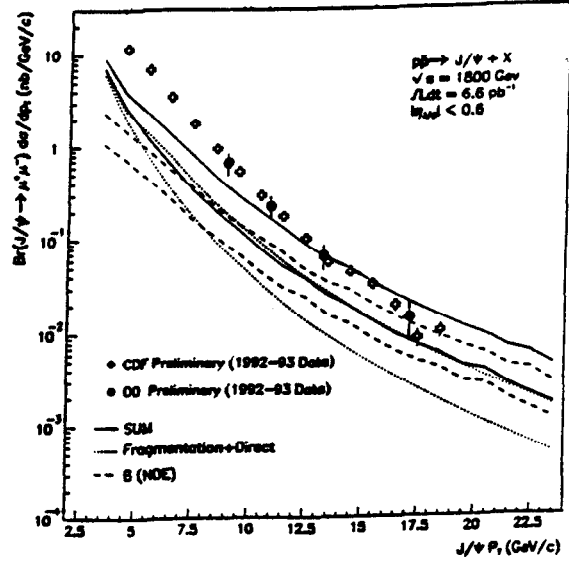

Figure 5. Inclusive J/ψ cross section a function of $P_t^{J/\psi}$.

cross section analysis described above. The dimuon was required to have oppositely signed muons, and $|\eta_w| < 0.6$. The number of J/ψ after all cuts was estimated by fitting the invariant dimuon mass distribution to the sum of a Gaussian centered at the J/ψ mass and a polynomial background (consisting mostly of sequential b-quark decays). The total number of J/ψ given by the fit was 414 ± 50 from data runs having a total integrated luminosity of 6.6 pb^{-1}. The overall J/ψ detection efficiency is a combination of trigger and offline efficiencies, and was determined using complete detector and trigger simulations. The number of J/ψ's in each p_t^ψ bin was determined from the fit described above. The inclusive cross section times branching ratio shown in Figure 5 was obtained by dividing the data bin by bin by the J/ψ detection efficiency and the integrated luminosity. The D0 data points are in good agreement with the CDF data [5]. Also shown are the theoretical estimates for J/ψ production from b-quark decay, and direct charmonium production [6] plus fragmentation processes. The measured inclusive ψ cross section is in reasonable agreement with the predicted contribution for the sum of these three sources at higher values of $P_t^{J/\psi}$, but there is considerable excess in the data at lower values of $P_t^{J/\psi}$.

3.1. Fraction of J/ψ from Direct Charmonium.

J/ψ's from direct charmonium production arise primarily through the decay of χ_c. The muons from χ_c are expected to be isolated, and are accompanied by a low E_t photon. Events with photons were tagged by requiring the presence in the event of an electromagnetic
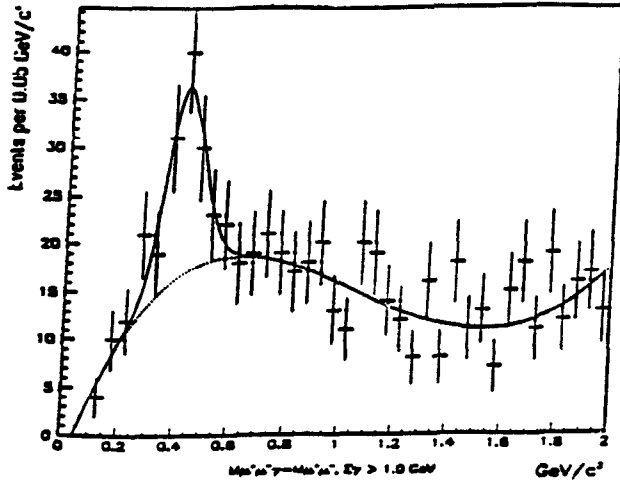
Figure 6. $M_{\mu\mu\gamma} - M_{\mu\mu}$ for the $\chi_c \longrightarrow J/\psi X$ sample.

Contribution	# of events
Υ	84 ± 11
Cosmics	7 ± 5
QCD	115 ± 14
Drell-Yan	33 ± 10

calorimeter cluster of energy $E_\gamma > 0.6$ GeV. Figure 6 shows the distribution of mass difference, $M^{\mu\mu\gamma} - M^{\mu\mu}$, with a peak at 0.43 GeV/c^2. The number of χ_c's predicted from the fit (after background subtraction) is $66 \pm 15 \pm 5$. Correcting this number by the photon detection efficiency and isolation efficiency gives a fraction of J/ψ with $P_t^{J/\psi} > 8$ GeV/c and $|\eta| < 0.6$ from χ_c decay equal to $0.30 \pm 0.07 \pm 0.10$, and for $P_t^{J/\psi} > 10$ GeV/c, $|\eta| < 0.6$, of $0.22 \pm 0.07 \pm 0.09$.

4. Inclusive Upsilon Cross Section

The data sample for the Υ analysis was selected from the same data as for the dimuon analyses described above. Since muons from Υ decay are expected to be isolated, at least one of the muons in each event was required to satisfy an isolation cut defined in equation 1. A simultaneous maximum likelihood fit to three distributions: dimuon mass, energy deposition in a wide cone of $R = 0.6$ minus the energy in cone of $R = 0.2$ about the muon (a quantity termed muon "halo"), and floating T0 (defined earlier in this note), was used to extract the number of Υ's from the background (QCD, Drell-Yan, and cosmic rays). The shapes used in the fit were derived from appropriate data samples, and in the case of the mass distribution, from Monte Carlo. The result of this fit is shown in Figure 7. The number of Υ's predicted in the sample from this fit was 84 ± 11. Table 4 shows the predictions from the fit for the numbers of events from the different sources contributing to the total sample.

Correcting N_Υ for the acceptance, the offline cuts, and the trigger efficiency, and the integrated luminosity of the sample, the total cross section times branching fraction to muons was calculated to be:

$$\sigma_\Upsilon \cdot BR(P_t(\Upsilon) > 1\text{GeV/c}, |\, y\, | < 0.7) = 1.15 \pm 0.13(\text{stat}) \pm 0.25(\text{sys})\text{nb}$$

To obtain a total cross section, a total branching fraction for the $1S$, $2S$ and $3S$ states (which D0 does not resolve) was calculated using Particle Data Group branching fractions [7], together with preliminary CDF cross sections [8] for these states:

$$BR(1S, 2S, 3S) = \frac{\sigma(1S) \cdot BR(1S) + \sigma(2S) \cdot BR(2S) + \sigma(3S) \cdot BR(3S)}{\sigma(1S, 2S, 3S)}$$

Bearing in mind that this total branching fraction is based upon cross sections which are themselves preliminary, the total Υ production cross section calculated in this manner is calculated to be

$$\sigma_\Upsilon(P_t(\Upsilon) > 1\text{GeV/c}, |\, y\, | < 0.7) = 57 \pm 6.2(\text{stat}) \pm 12.5(\text{sys})\text{nb}$$

5. Conclusions

The b-quark cross section measured by D0 in the region $|\, y_b\, | < 1$ is in agreement, within the range of experimental error and theoretical uncertainty, with the next-to-leading order QCD prediction [4]. However, the data points are systematically high with respect to that prediction. The inclusive J/ψ and Υ cross sections in the regions $|\, y_\psi\, | < 0.6$ and $|\, y_\Upsilon\, | < 0.7$ are also high respect to prediction [6,9].

6. References

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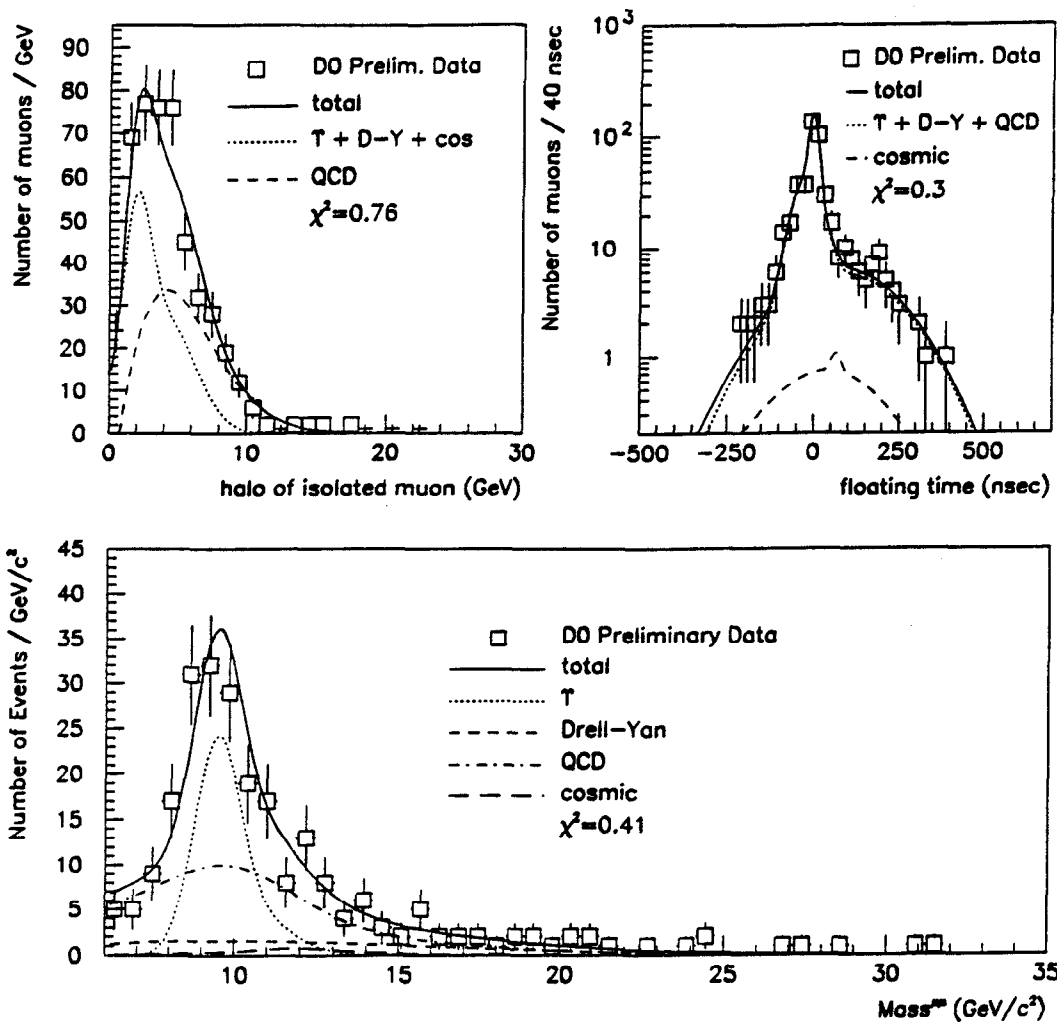[2] C. Albajar et al. Phys. Lett. **B186** (1987) 237.

Figure 7. Result of simultaneous fit to the mass, T0, and Halo distributions in the Υ sample.

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